# ROPEC – ROtary PErcussive Coring Drill for Mars Sample Return

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## Abstract

The ROtary Percussive Coring Drill is a light weight, flight-like, five-actuator drilling system prototype designed to acquire core material from rock targets for the purposes of Mars Sample Return. In addition to producing rock cores for sample caching, the ROPEC drill can be integrated with a number of end effectors to perform functions such as rock surface abrasion, dust and debris removal, powder and regolith acquisition, and viewing of potential cores prior to caching. The ROPEC drill and its suite of end effectors have been demonstrated with a five degree of freedom Robotic Arm mounted to a mobility system with a prototype sample cache and bit storage station.

## Introduction

The mobility platform for the recently announced surface mission to Mars launching in the year 2020 is based on the Mars Science Laboratory rover [1]. This rover will conduct rigorous in-situ science assessments of the Martian surface with the goals of characterizing the local geology, looking for signs of an ancient habitable environment, and searching for signs of ancient life on the red planet. In addition to these science goals, the Mars 2020 mission will also acquire a number of physical samples, storing them within a sample cache for potential return to Earth at a later stage. These samples will likely include rock cores, regolith samples, and atmospheric gas. The ROtary PErcussive Coring (ROPEC) Drill has been designed to meet the needs of a Mars Sample Return mission by providing a platform that can produce rock cores, powder and regolith samples, and can abrade the surface of rocks. This last function serves to remove the weathered layer and expose a fresh rock face similar to the Rock Abrasion Tool on the Mars Exploration Rovers [2]. These functions are accomplished using a variety of bits, most of which can then be inserted into a Sample Cache within the rover body for storage.

The ROPEC Drill is the latest in a series of rock coring mechanisms aimed at planetary exploration developed by Honeybee Robotics over the past two decades [3]. The ROPEC Drill design builds on previous drilling systems such as the Mini Corer, Corer Abrader Tool, and SASSI Drill; improving upon them to achieve a light weight, compact, and highly capable mechanism. This drill can be mounted to a multi-degree of freedom robotic arm similar to the Instrument Deployment Device on the Mars Exploration Rovers or the Robotic Arm on the Mars Science Laboratory. A robotic arm is used to place the ROPEC drill on the desired rock target, holding the drill in position using a pair of preload tines. The ROPEC Drill then utilizes a rotary percussive action which can penetrate a wide range of rock targets ranging from high strength basalts to highly porous low strength sedimentary rocks. Once the drill has reached its target depth, an internal mechanism shears the rock core at the base of the drill bit. This shearing action simultaneously separates the core from the base rock and captures the core within the bit; preventing it from falling out while the bit is retracted from the rock. The entire drill bit, with rock core inside, can then be delivered to the Sample Cache.

This paper focuses on lessons learned throughout the design and development of the ROPEC Drill, as well as distinctive design features and the decisions and testing that contributed to their final implementation. There are a number of unique design features on the ROPEC Drill which should be brought to the attention of the spacecraft mechanisms community. These features could be used on future space flight mechanisms and prototypes. An overview of the ROPEC Drill and its operational usage

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is discussed below, followed by details of the design which are critical for understanding the lessons learned and any unique mechanism features. The objective of this publication is to provide detailed information on the design of the ROPEC Drill, focusing on educating future mechanism designers of similar devices. This work was funded by the National Aeronautics and Space Administration (NASA) Planetary Instrument Definition and Development Program.

## Driving Requirements

The ROPEC drill is designed to support a “One Bit-One Core” approach to delivering rock samples to a sample return canister [4]. This method dedicates a single drill bit to the acquisition of each returned rock core, as shown in Figure 1. After the core has been separated from the base rock and captured within the drill bit, the entire bit is delivered to and stored within the sample cache in an enclosed casing, to ultimately be returned to Earth. This method simplifies the process of caching rock cores by eliminating additional mechanisms required to extract rock cores from drill bits and place them within sealed canisters. The “One Bit-One Core” technique lead to one of the driving requirements on the ROPEC drill which was the ability to autonomously change end effectors. Since each core would have a dedicated drill bit for sample caching, the ROPEC drill and its bits have been designed with dedicated tool change features. This also allows for alternate end effectors, such as the Rock Abrasion Brushing Bit (RABBit), Powder and Regolith Acquisition Bit (PRABit), and Core PreView Bit. The ability to change bits drives many aspects of the ROPEC design.

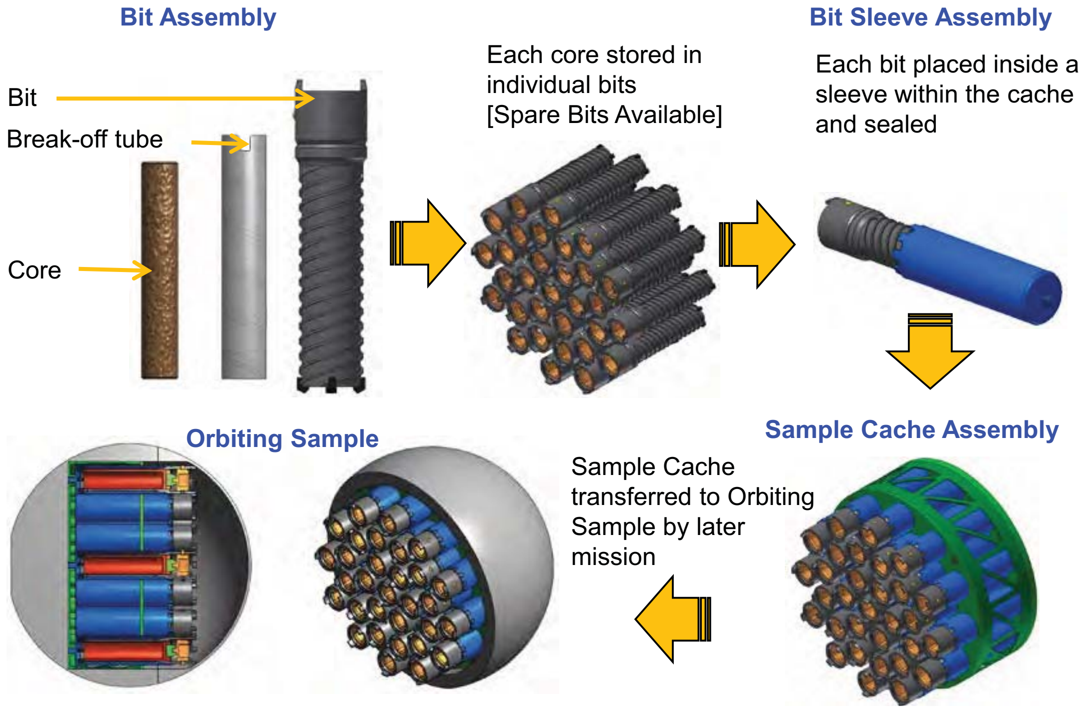

**Figure 1. “One Bit One Core” Mars Sample Return Architecture**

The “One Bit-One Core” architecture also requires that each drill bit be as light weight and volume efficient as possible to ensure that they could be returned to Earth at a later stage. At present, the return of the cached samples has not been explicitly defined as a mission by NASA. However, if approval for the mission is obtained, it will likely consist of two separate missions [5]. The first mission will consist of a Lander, Fetch Rover and a Mars Ascent Vehicle. Landing close to the sample cache, the small Fetch Rover would drive to the cache, retrieve it, and return it to the Lander, where it would be placed inside the Orbiting Sample (OS) within the Mars Ascent Vehicle (MAV). The MAV would then launch from the surface, escape Martian gravity, and jettison the OS into Mars orbit. The second mission would retrieve the OS some time later and return it to Earth onboard an Earth Entry Vehicle. While the design of the MAV has not been finalized, Volume and Mass dedicated to the Sample Cache and OS is likely to be highly constrained. This drives the Bit Assembly to be as small in diameter and length and as low mass as possible. The small form factor of the bit is a significant driver on the allowable size of internal components within the ROPEC drill.

An animation showing this Mars Sample Return architecture is available at the following URL:
http://www.youtube.com/watch?v=NphWPvi9cy4

Another driving requirement on the ROPEC design was the ability to lock the Auger stage rotation position during the Core Breakoff routine. Previous coring drill designs have had difficulty shearing rock cores, particularly in high strength igneous rocks. It was found that rotation of the bit inner shearing tube within the main drill bit would sometimes cause the latter to rotate with the shearing tube due to friction between the tubes overcoming the Auger actuator holding torque. This would negate the breakoff effect, and simply cause the entire bit to spin around the rock core, which was still attached to the base rock. For this reason, the SASSI drill was the first coring drill to implement an Auger Locking Mechanism to lock the position of the Auger during the breakoff sequence. This requirement has since been implemented on the ROPEC drill and all other Honeybee Robotics coring drills that use the eccentric tubes method of breaking off rock cores. This requirement is a significant design driver for the ROPEC drill.

Lessons learned from previous Honeybee Robotics developed coring drills suggested that the core breakoff mechanism worked well in shearing the rock core from the base rock, but that core quality needed to be improved in order to maximize science return. Figure 2 illustrates a number of different rock cores collected using Honeybee Robotics' SASSI Drill, showing the range of core quality obtained. While core quality depends on a number of different factors including rock type, internal bit clearance and cutter design, one of the ways to minimize the chance of low grade cores is to couple the Bit Breakoff Tube rotation with respect to the Bit Auger Tube during drilling. These two are then decoupled during the core breakoff routine so that the Bit Breakoff Tube can be rotated with respect to the Bit Auger Tube. The SASSI drill did not initially have this capability and thus was more likely to produce lower quality cores. The prerequisite to couple and decouple these tubes within the drill bit is one of the driving requirements in the ROPEC design. This eccentric tube core breakoff mechanism is explained in further detail in the following sections.

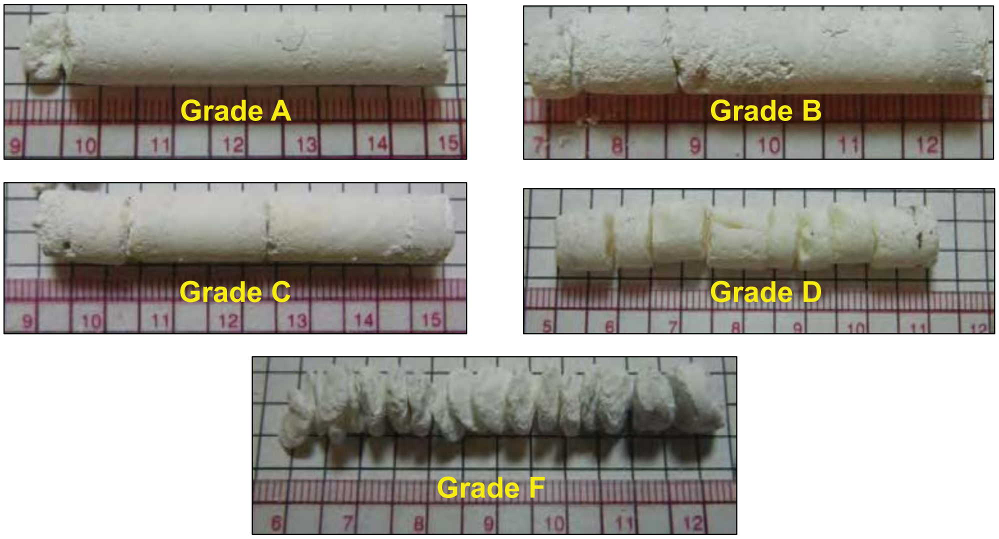

Figure 2. Core Quality Grading Scheme

Another significant design driver is the ability to separate the Auger rotary drivetrain from the Percussive hammer system. Rotary only drilling is ideal for weak rocks or while performing a hole-starting routine, while rotary-percussive drilling is best suited for penetrating harder rocks but may ruin a softer rock sample. Hammering action alone can be used for hole starting routines in rocks with steeply sloped or very rough surfaces. Hammering alone can also be used to dispense regolith, powder, and cores, if desirable. These operational modes were successfully demonstrated on previous drilling systems, leading to the requirement to separate Auger rotation from Percussive hammering.

In addition to various performance requirements (Auger speed greater than 350 RPM, percussion frequency of 1500 BPM, percussive energy greater than 0.5 Joules, breakoff torque greater than 10 Newton-meters, weight on bit greater than 40 Newtons) dictated by previous successful rotary percussive drilling systems, the mass of the ROPEC drill was desired to be less than 4 kg. During the requirements derivation phase, the Mars Sample Return architecture at the time assumed that the drilling and caching rover would be slightly larger than the Mars Exploration Rovers. This rover would use a Robotic Arm similar in design but larger than the Instrument Deployment Device (IDD) on the Mars Exploration Rovers (MER). The IDD has an approximately 2-kg end of arm payload capacity, and it was estimated that a drill weighing less than 4 kg could be deployed using a robotic arm suitable for the larger, MER Plus rover. After completing design and assembly of the ROPEC drill in December of 2012, it was announced that the initial drilling and caching rover would utilize a Mars Science Laboratory rover, which enables a significantly larger Robotic Arm and end of arm payload. While mass is no longer a significant design driver, during the development phase, it was critical that the ROPEC drill be as light weight as possible. As a result, the ROPEC drill mass is less than 4 kg.

## Design Discussion

### Mechanism Overview

The ROPEC Drill is a flight-like prototype, five actuator system. Four of these actuators are mounted to a linear translation stage driven by a ball screw. These actuators are used to drive the Auger axis, Breakoff mechanism, Percussive system, and Pushrod mechanism. The linear translation stage is driven by the Z-Axis actuator. The ROPEC Drill uses these actuators, as well as a number of electronic sensors to perform various tasks, described as follows. Figure 3 illustrates the ROPEC drill and its corresponding actuators with the latest flex cable design and Figure 4 shows the fully assembled drill with standard cable harnesses and a cable guide.

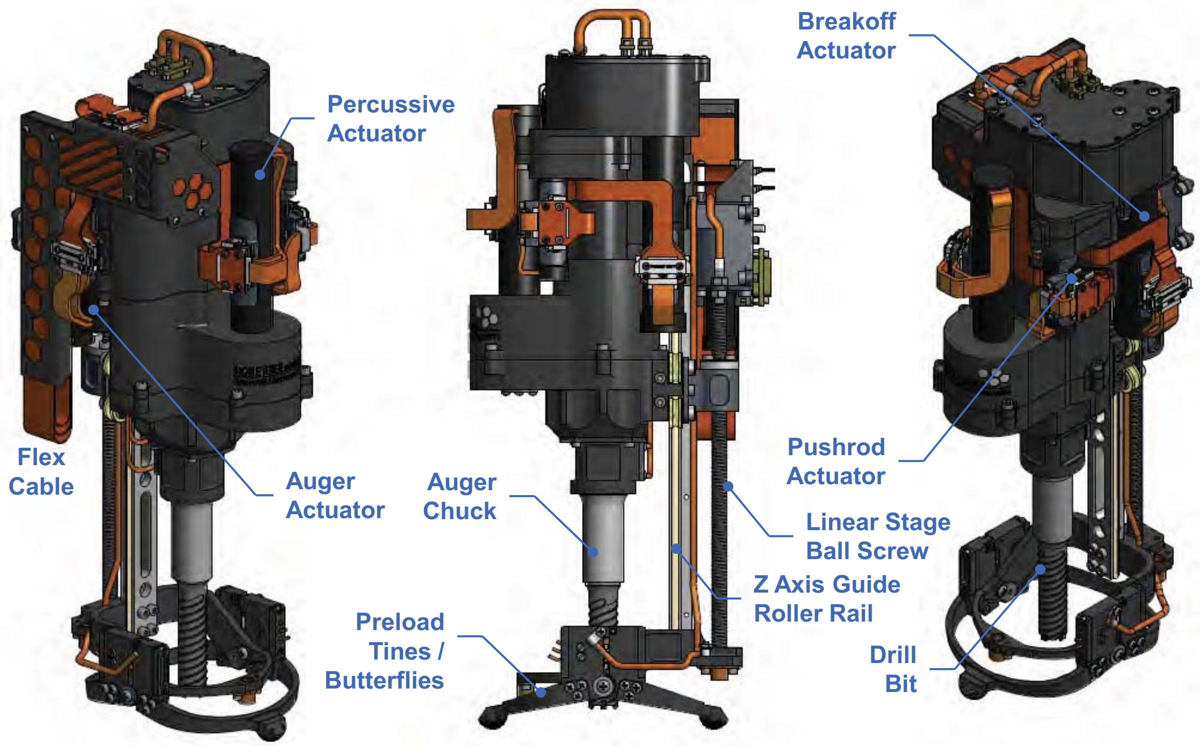

**Figure 3. ROPEC Drill Design with Revised Flex Cable**

- Auger Actuator – The Auger actuator is the primary driving force behind the drilling action. The drill bit is connected to the auger and needs to rotate continuously during drilling. The auger axis can be locked in position during the core breakoff routine where the rock core is sheared from the base material. The absolute position of the auger's output can be determined using a reed switch and a magnet located on the auger output shaft.

- Breakoff Actuator – The Breakoff actuator is not used during the drilling process. During the core breakoff routine, the Breakoff actuator uses a high gear reduction to shear the core. Due to the high gear reduction, this actuator is normally not engaged with the drill output drivetrain during drilling; however an automated gear meshing routine is used to couple the Breakoff actuator to the drill output drivetrain during the core breakoff routine. This eliminates excessive drag torque associated with back-driving the high-reduction Breakoff Actuator while drilling.

- Percussive Actuator – The Percussive actuator drives a cam, spring, and follower mechanism that produces high-frequency, high-impact loads on the auger output shaft. The percussive wave from these impacts is then transferred through the drill bit down to the cutting elements and into the rock. The percussive mechanism uses a helical rotating cam to drive a rotating follower that is spring preloaded against the internal drill housing. As the helical cam rotates, it contacts the follower, which rolls along the surface of the cam until it reaches a drop off point. At the drop off point, the follower is released, and the potential energy stored in the spring is used to create the percussive impact by way of a hammer and anvil arrangement.

- Pushrod Actuator – The Pushrod actuator is used to control a long pushrod within the center of the ROPEC Drill. In a previous Mars Sample Return architecture developed by Honeybee Robotics, it was determined that a pushrod could be useful for inserting the drill bit and rock core into the Sample Cache. In the current "One Bit-One Core" architecture, it is no longer required. While the pushrod has the capability to extend far outside the drill, it is also used in a number of internal routines, such as locking the auger axis during core breakoff, and coupling the breakoff actuator to the output drivetrain while shearing the core.

- Z Axis Actuator – The Z-Axis actuator drives a precision ball screw which controls the depth of penetration of the drill bit during drilling operations. Motor current feedback from the actuator can be used to estimate weight on bit. A non-contact inductive proximity sensor is used to home the linear extension stage.

- Preload Tines – The Preload Tines, or “Butterflies” are used to stabilize the ROPEC drill during drilling. These tines are placed on a rock surface, and a pair of limit switches within the Butterflies provides feedback as to whether the tines have made contact. Once contact is confirmed, the Robotic Arm continues to preload the tines against the rock, stabilizing ROPEC for drilling operations.

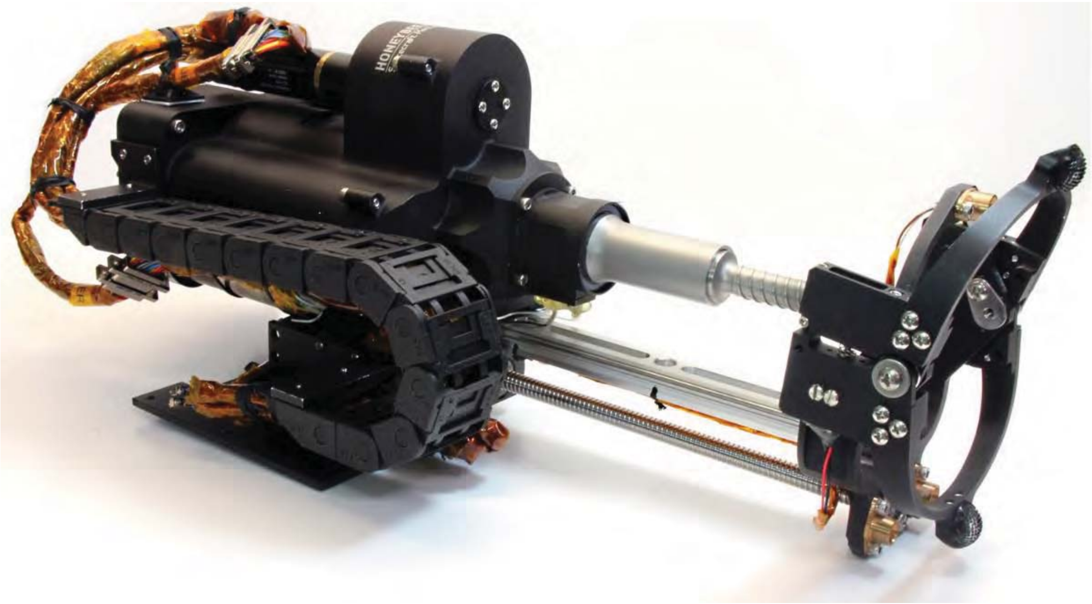

**Figure 4. Assembled ROPEC Drill without Flex Cable**

Auger Subsystem Design

The ROPEC Auger sub-system is shown in Figure 5. The maximum auger output speed is 375 RPM. The 90 Watt Auger Actuator (1) transmits power to the Auger Gear (4) through a system of Idler and Transfer gears. The Transfer Gear (3) also has a tab feature which allows it to lock, preventing the auger drive train from moving in one direction. Locking the Auger drivetrain is accomplished by allowing the torsion spring-loaded Auger Lock (6) to pivot into position, where it eventually contacts a tab on the Transfer Gear; temporarily acting as a hard stop. During drilling, the Auger Lock is pivoted out of the way of the Transfer Gears locking tab. This allows the Auger drivetrain to spin continuously. Pivoting of the Auger Lock is performed by raising and lowering the position of the Auger Locking Cam (7), which is controlled by the position of the Pushrod, as discussed in follow on sections.

Calculations were performed to size the actuator and drivetrain based on previous drilling data obtained using a similar drilling system. As shown in Figure 5, the Auger Transfer Gear transmits power from the Auger actuator to the Auger Gear (4). A spline in the Auger Gear (not shown) transmits torque to the Auger Chuck, while allowing the Chuck to slide axially over a short distance. With the Auger Chuck connected to the Drill Bit, this axial motion is necessary in order to allow impact energy from the percussive system to be transmitted to the Drill Bit without significant losses. A spring energized seal (5) around the Auger Chuck prevents debris from migrating into the mechanism.

The Auger Gear is constrained with a duplex pair of angular contact bearings which support Weight on Bit loads. While the Auger Chuck (12) is free to slide within the Auger Gear along the spline connection, it is constrained on one end by a flange on the chuck itself, and by a thrust needle bearing below (11).

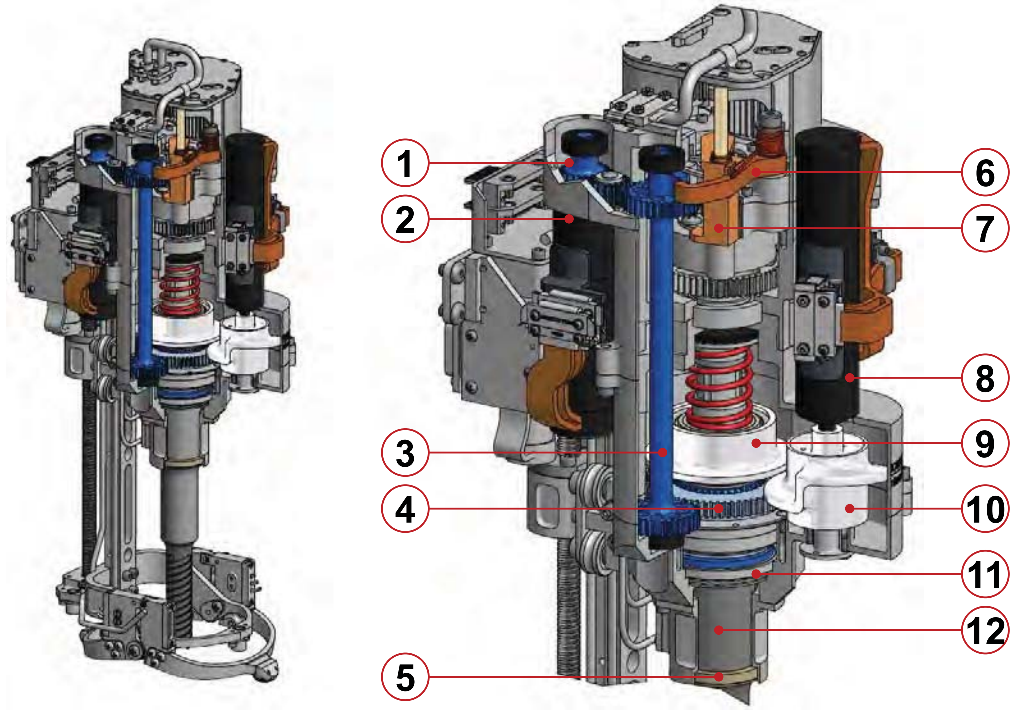

**Figure 5. ROPEC Drill Auger Subsystem (1) Auger Pinion Gear (2) Auger Actuator (3) Auger Transfer Gear (4) Auger Output Gear and Spline (5) Auger Dust Seal (6) Auger Lock (7) Auger Locking Cam (8) Percussive Actuator (9) Percussive Follower and Hammer (10) Percussive Cam (11) Thrust Needle Bearing (12) Auger Chuck**

<u>Percussive Subsystem Design</u>

The 100-Watt Percussive Sub-System delivers 0.56 Joule per blow at up to 1500 blows per minute and is also shown in Figure 5. The percussive system uses a helical Percussive Cam (10) which is driven by the Percussive Actuator (8). As the helical cam rotates, it raises a Percussive Follower and impact Hammer (9), preloading a spring. The helical cam raises the follower for approximately 3/4 of its revolution, and then releases it. Once released, the follower and impact hammer contact the top surface of the Auger Chuck, sending a percussive wave through the chuck and drill bit, ultimately impacting the rock surface. The Percussive Follower is mounted on preloaded angular bearings which allow the follower to rotate relative to the hammer. This rotation is critical in order to reduce friction and wear between the cam and follower. The hammer utilizes a custom ball spline, allowing it to move axially with minimal frictional losses.

The cam and follower percussive system has been employed in all of Honeybee Robotics' rotary-percussive drills. The percussive system in the SASSI drill has been successfully operated for 2 million cycles in a vacuum chamber at Mars pressure, which is equivalent to approximately 19 hours of operation.

<u>ROPEC Breakoff Subsystem Design</u>

The ROPEC Breakoff subsystem uses two nested tubes to shear the rock core at the bottom, and capture it for extraction from the base material [7]. The outer tube forms the main drill bit consisting of the bit shank, which connects to the ROPEC Auger Chuck, the helical fluting for cuttings removal and the tungsten carbide cutters at the base. The center bore of this outer tube is offset from the central axis of the exterior of the bit. The bore of the inner tube has the same offset. When the tubes are nested together, they can be aligned such that the bore of the inner tube is coaxial with the outer surface of the outer tube. During the drilling process, these tubes are in this orientation, and need to spin simultaneously to avoid prematurely shearing the core.

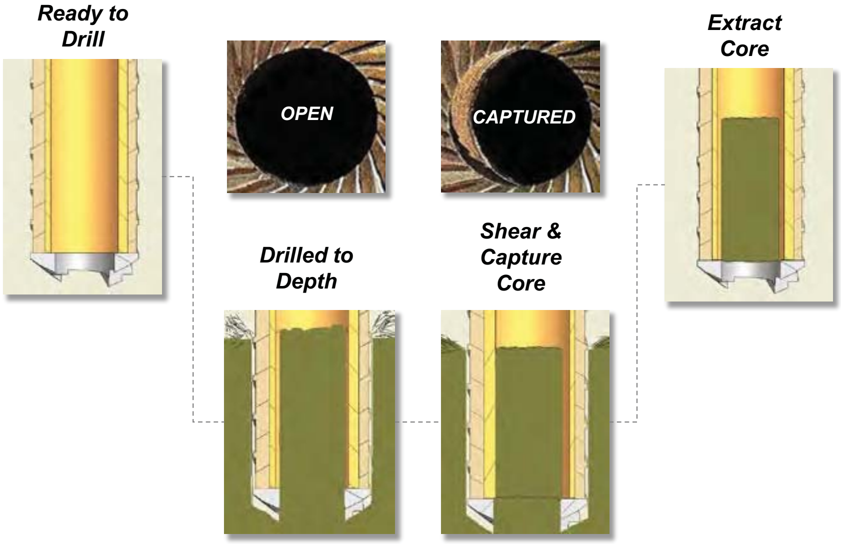

Figure 6. Core Breakoff Method

When core breakoff is desired, the outer tube is held stationary, while the inner tube is rotated using the Breakoff Shaft. This rotation shifts the bore of the inner tube relative to the central axis of the outer tube. This small shift is enough to shear the rock core at the base, and also capture it inside the bit, preventing it from falling out during extraction from the base material. This process is illustrated in Figure 6. This method is patented by Honeybee Robotics and has been used on a number of successful coring drill designs.

A recently concluded study with the SASSI drill and 140 coring tests in several rock types has shown that the inner breakoff tube successfully sheared and captured cores in 94% of cases, while partial core loss was observed in 6% of tests [8]. No full length core loss was observed. Some of the cores successfully captured included the “F” grade cores shown in Figure 2.

The Breakoff subsystem is shown in Figure 7. This drivetrain has the ability to selectively mesh and de-mesh the main Breakoff Output Gear (3). This subsystem is designed to produce enough torque to shear a rock core. This high torque is based on data from similar mechanisms, including a comfortable amount of torque margin. Due to this high torque requirement, the planetary gearhead on the breakoff motor has a multiple stage reduction, making the back-drive torque very high. Since the breakoff shaft needs to be coupled to the auger shaft during drilling, if the breakoff drivetrain were permanently coupled to the motor, the auger actuator would need to back-drive the breakoff motor. This back-driving rotation would require a prohibitively large amount of torque, which would result in a significantly larger auger actuator. The solution to this problem is to selectively decouple the breakoff drivetrain from the main breakoff shaft. This is accomplished by moving the Breakoff Cluster Gear (2) axially to de-mesh the drivetrain during drilling, and mesh the drivetrain during core breakoff. A magnetic Absolute Position Sensor (6) is used to provide position feedback to the control system, telling it exactly what position the breakoff drivetrain is in so that gear meshing is performed smoothly. The Breakoff Cluster Gear is translated using the Pushrod sub-system.

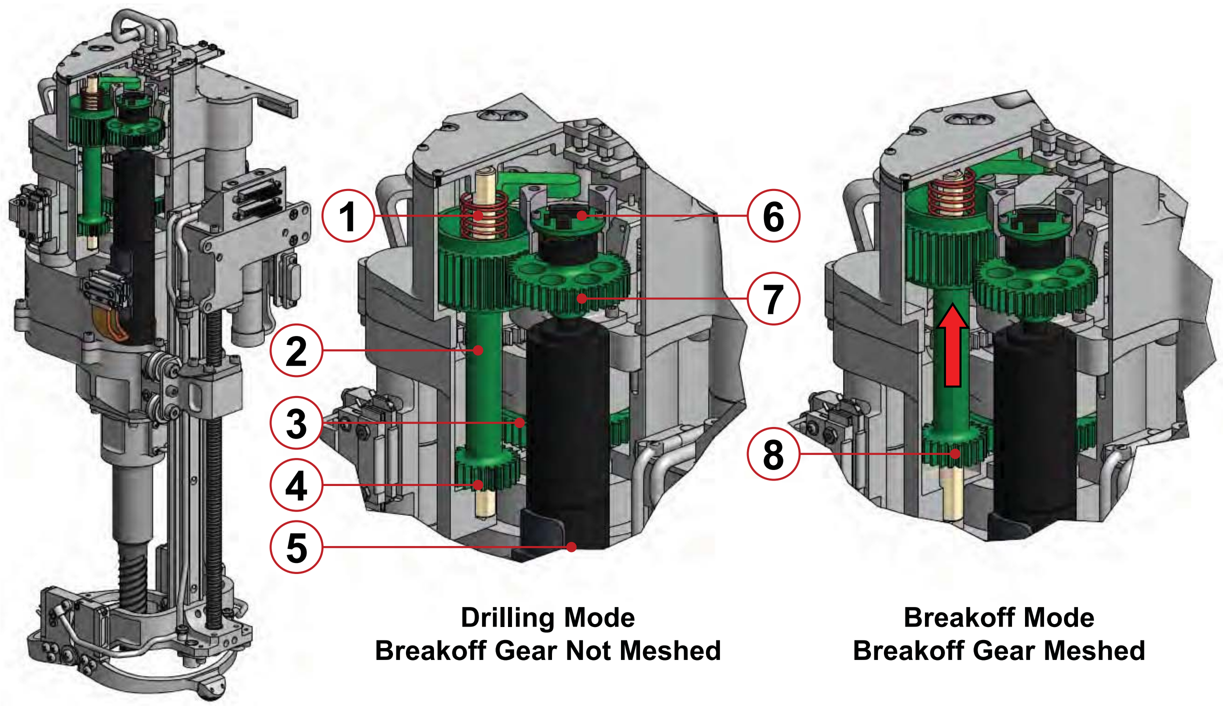

**Figure 7. ROPEC Drill Breakoff Subsystem (1) Return Spring (2) Breakoff Cluster Gear (3) Breakoff Output Gear (4) Non-Meshed Gears (5) Breakoff Actuator (6) Absolute Position Sensor (7) Breakoff Pinion Gear (8) Meshed Gears**

ROPEC Pushrod Subsystem Design

The Pushrod subsystem is shown Figure 9. In a previous iteration of the "One Bit-One Core" architecture, a pushrod was necessary in order to load a drill bit containing a rock core into the sample cache for sample return. The current "One Bit-One Core architecture does not require a Pushrod any longer, however due to the original requirement, a Pushrod with a long stroke has been included in the ROPEC design. The pushrod system uses a 1/4-28 threaded leadscrew and nut arrangement. The Pushrod Actuator drives a series of gears, which ultimately rotates the Pushrod Nut (5). As the Pushrod Nut rotates, the threads cause the Pushrod (1) to move axially. The Pushrod Ground Tube (3) is connected to the surrounding housing structure. The Pushrod is keyed rotationally with respect to the Ground Tube but is able to slide axially relative to it.

In addition to the option of pushing a drill bit into a sample cache, the Pushrod also helps actuate a number of different mechanisms within the ROPEC drill itself. The Pushrod is shown in both the drilling position and in its fully extended position in Figure 9. Once drilling is complete, the Pushrod is retracted further into the drill. This motion raises the Auger Locking Cam (Component 7 as shown in Figure 5), which actuates the Auger Lock (Component 6 as shown in Figure 5) near the top of the drill, which locks the Auger Transfer Gear in place, preventing the Auger drivetrain from rotating during the core breakoff routine, as described previously.

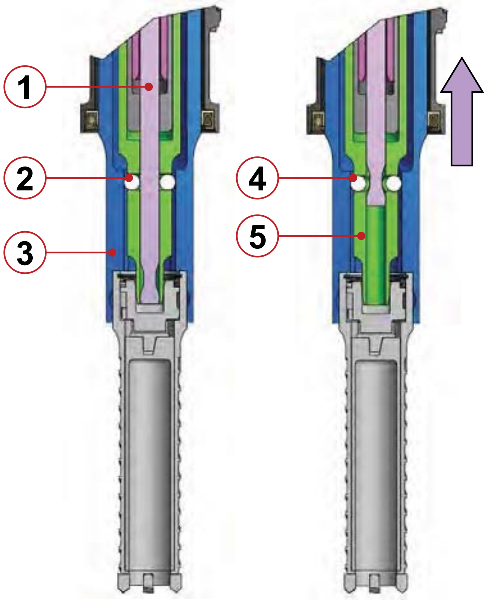

**Figure 8. ROPEC Drill Pushrod Subsystem (1) Pushrod (2) Locked Balls (3) Auger Chuck (4) Unlocked Balls (5) Breakoff Shaft**

As the Pushrod is retracted still further into the drill, it de-couples the Auger Chuck from the Breakoff Shaft as shown in Figure 8. During the drilling routine, the Auger Chuck (3) and Breakoff Shaft (5) are coupled together by way of a pair of locking balls held in place by the Pushrod (1). After drilling is complete, the Pushrod is retracted upwards until the balls are unlocked by “falling into” a groove in the Pushrod (4). This decouples the Auger Chuck from the Breakoff Shaft, allowing the latter to rotate relative to the chuck so that the rock core can be sheared.

Finally, as the Auger Chuck and Breakoff Shaft are decoupled, this movement raises the Breakoff Cluster Gear (Component 2 as shown in Figure 7), engaging the teeth with the main Breakoff Gear (Component 3 as shown in Figure 7) as previously described. The drill is now ready to break off a core.

While the Pushrod is no longer necessary in the “One Bit-One Core” architecture, it serves an important role in the ROPEC Drill by actuating a number of critical mechanisms.

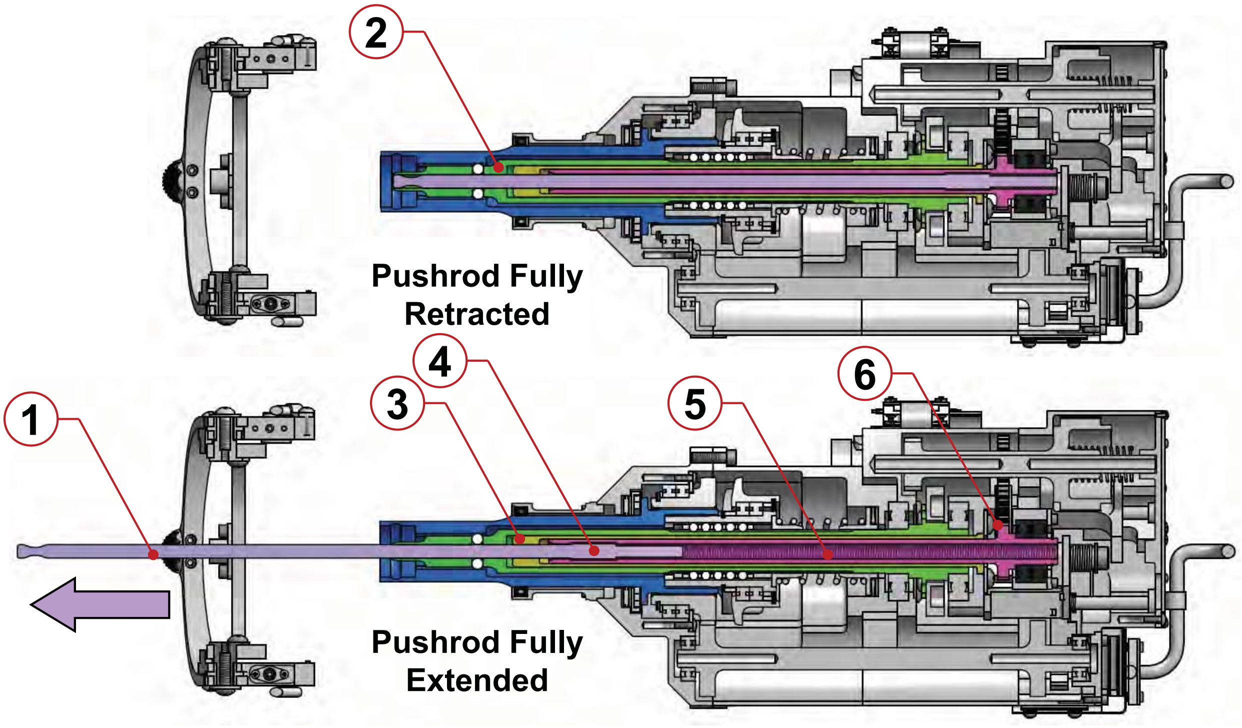

**Figure 9. ROPEC Drill Pushrod Subsystem (1) Pushrod (2) Breakoff Shaft (3) Ground Tube (4) Pushrod Threaded Section (5) Pushrod Deep Threaded Nut (6) Pushrod Output Gear**

<u>ROPEC Butterfly Subassembly Design</u>

The Butterfly sub-assembly design is based on a similar mechanism on the MER Rock Abrasion Tool, and is shown in Figure 10. This sub-assembly is connected to the base of the Z-Axis Guide Roller Rail. The Butterfly sub-assembly allows the ROPEC drill to be placed on the surface of a rock at an angle of up to 15 degrees from the local surface normal of the target. This angle is limited by mechanical Angular Hard Stops (3). Once placed on the target, the Butterfly sub-assembly is preloaded against the rock to help stabilize the drilling process. Contact Tines (2) have a raised diamond pattern knurl feature on them to help grip uneven rock surfaces.

The Butterfly sub-assembly utilizes two micro Contact Switches (1) for redundancy. These switches can be used by the control system as a safeguard in case the drill loses preload during an operation. A change in state of the contact switch might indicate that preload was lost, or the drill slipped off the rock surface.

A compression spring keeps the switches normally open. As the Butterfly is preloaded against a surface, the spring is compressed, and the switches are closed. The Butterfly sub-assembly also includes a set of three Alignment Cup (5) features. Currently these features are designed as simple tapered bushings. These bushings can be used to mate with a Bit Storage Station or Sample Cache, providing a more accurate interface.

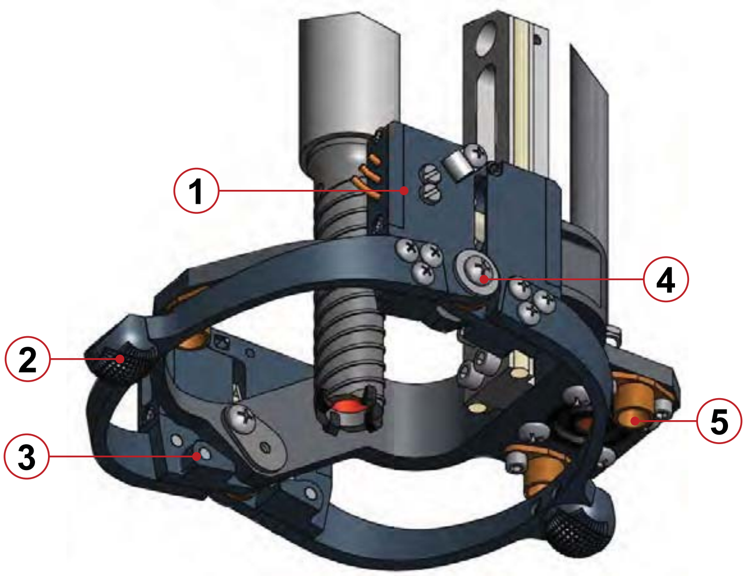

**Figure 10. ROPEC Drill Butterfly Subsystem (1) Contact Switch Housing (2) Contact Tine (3) Angular Hardstop (4) Pivot Shaft / Bushings (5) Alignment Cups**

ROPEC Z Axis Subassembly Design

The Z-Axis sub-assembly utilizes an off the shelf ballscrew and nut, as well as an off the shelf linear rail and rollers. The ballscrew is driven by a set of spur gears, and a felt seal prevents debris from migrating into the drivetrain housing. The ballscrew itself has a set of seals which seal the nut, preventing debris from jamming the reciprocating balls. An inductive proximity sensor is used as a limit switch to home the Z-Axis mechanism, providing a consistent starting position. A thin strip of sheet metal is cantilevered off of the moving carriage. This strip of sheet metal triggers the Proximity Sensor.

ROPEC Flex Cable Design

In order to consolidate cabling on the ROPEC drill, a custom flex cable was designed. A set of two almost identically shaped flex cables are laid on top of one another with a third cable in between to act as shielding. One flex cable has traces for motor power, and the other for encoder and hall sensor signals.

A detailed investigation was performed early in the design process to determine the amount of layers required on each flex cable. More layers typically results in a higher cost of the flex cable, as well as a stiffer cable with a larger bend radius. It was important that the flex cable have a low stiffness in this design because the flex cable needs to bend as the drill head is moved along the length of the Z-Axis Guide Rail. To keep the overall volume of the drill low, it was desirable to have as small a bend radius as possible. To perform this analysis, the number of wires for each motor, limit switch and other sensors was tabulated, along with the peak electrical current which that wire was expected to experience. Using the peak expected current, a maximum copper trace width was determined, based on standard industry practice for flex cables and printed circuit boards. Adding all of these widths together and accounting for gap space between each trace, the required width of the flex cable was determined.

ROPEC End Effectors

The ROPEC Auger Chuck is able to autonomously lock and unlock a drill bit. With this ability, and the degrees of freedom available, a number of end effectors have been designed to increase the versatility of the ROPEC Drill to different mission architectures. These end effectors are shown in Figure 11 and discussed as follows. These end effectors are demonstrated in the video at the URL below.
http://www.youtube.com/watch?v=VhfL3htrtZ8

**Figure 11. ROPEC Drill End Effectors (1) Standard Coring Bit (2) Rock Abrasion Brushing Bit (3) Powder and Regolith Acquisition Bit (4) Core PreView Bit (5) Slot Bit**

1. Standard Coring Bit – The current ROPEC Coring Bit is designed to obtain a 1-cm diameter by 5-cm rock core. This size was based on Mars Sample Return requirements at the time of requirements definition. Honeybee Robotics has also developed a BigTooth cutter arrangement [3] where a single larger tooth cuts the outer diameter of the core. This allows the rock core to be ejected using a combination of gravity and drill percussion.
2. Rock Abrasion Brushing Bit (RABBit) – The RABBit adds rock abrasion and brushing capability to the ROPEC similar to the Rock Abrasion Tool on the MER rovers. The RABBit allows the ROPEC Drill to penetrate through the weathered surface rind of Martian rocks, allowing science instruments to view the actual rock composition. The RABBit can also be integrated with a small scoop for capture and delivery of abraded rock cuttings, rock cuttings remaining from a drilling operation, or surface regolith.
3. Powder and Regolith Acquisition Bit (PRABit) – The PRABit is a full-faced drill bit attachment that can be used to collect drill cuttings or regolith samples. Cuttings from the drilling process are transported up the drill flutes and into a collection chamber. The internal sleeve collection chamber can be fully open, fully closed, or rotated to expose up to two different sized sieve screens, such as a 1-mm or 150-micron screen. Using the sieve screens, powder can be delivered to science instruments at a desired size fraction. A prototype bit has been successfully tested in five different rock powders [9].
4. Core PreView Bit – This bit enables science instruments and imaging systems to view a small core from a rock target before the decision is made to cache a full length core. Once a core is acquired, the PreView Bit “window” can be exposed through rotation of the inner sleeve to view the core. Figure 11 shows the PreView window partially open with a core inside.
5. Slot Bit – This bit allows science instruments and imaging systems to view a small width of the core along its entire length prior to caching the Slot Bit in the Sample Cache. This allows mission planners to have a better understanding of the quality of core that they will ultimately return to Earth. Figure 11 shows the Slot Bit fully open with a partially fractured core inside.

## Mechanism Design and Test Lessons Learned

### Flex Cable Design

As shown in Figure 3, the ROPEC Flex Cable makes a number of complex bends in order to reach four actuators. In the first iteration of the design, not all of the connectors were on one side of the flex cable. This was not communicated appropriately to the team responsible for fabricating the flex cable, and it was assumed that all connectors were on the same side. Prior to integrating the flex cable with the control system, a pin-to-pin continuity test was performed, and the results showed that the main input connector pins were “mirrored” from what they needed to be. Fortunately, this was caught prior to attempting to run the actuators, and a new cable was made between the controller and the mirrored connector.

> *Lesson Learned: Be very careful when designing flex cables with multiple bends and changes in direction. Make sure that the engineers designing the cable routing properly communicates what side of the flex cable the connector is mounted on to the team responsible for mounting the connectors. During assembly, always perform a full continuity test on the flex cable, just like any other cable, even if the manufacturer guarantees that it was made according to specifications. It is always possible that the specifications inadequately described the connector locations.*

On the first iteration of the Flex Cable, the two 51 pin connectors were not properly strain relieved to the flex cable. The connectors were soldered directly to the flex cables, but no other strain relief was provided. The connectors were then screwed into a base structure, which offered the strain relief. Any time the connector was removed from the base structure during the assembly and debugging process, there was no longer anything providing strain relief between the connector and flex cable. This ultimately resulted in debonding of the connector from a number of the solder pads.

> *Lesson Learned: Always provide a permanent mechanical strain relief method between connectors and a flex cable, even if the cable will later be integrated into a structure that provides strain relief. The second iteration of the flex cable is shown in Figure 12. This was designed to have permanent metallic backing plates (2) attach the flex cable (3) to the 51 pin connector (5) using fasteners (1). This backing plate would be fabricated, and then sent to the vendor integrating the connector to the flex cable. The vendor would then mount the backing plate and verify continuity before delivery. After receiving the flex cable, this backing plate never has to separate from the flex cable again. The backing plate itself is then fastened to the drill structure (4) using fasteners (6). This results in a permanent strain relief between the connector and the flex cable. The 51 pin connector is then mated with the controller cable (7). Currently, the design of the second flex cable iteration has not been integrated into the ROPEC Drill.*

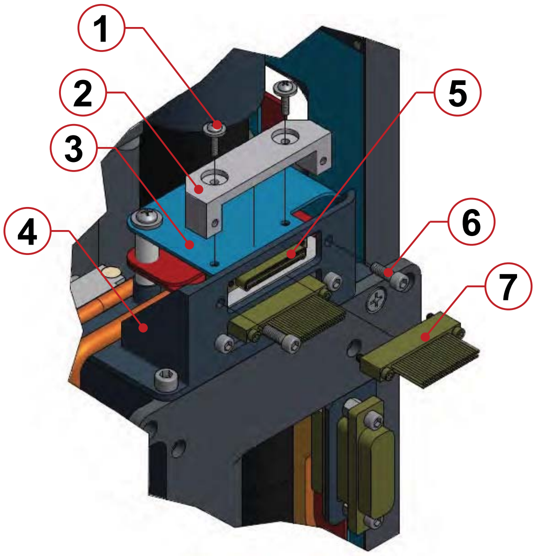

**Figure 12. Revised ROPEC Flex Cable Connector Strain Relief**

Coatings under High Contact Stress

The ROPEC percussive axis uses a hardened helical cam and rotating follower arrangement to preload and release a spring loaded impact device. This mechanism experiences over 10,000 cycles during one drilling operation alone. The majority of contact between the cam and follower is rolling contact, with a small amount of sliding contact as the follower climbs the “ramp” of the cam, and a moment of impact when the follower first contacts the cam. In an attempt to reduce friction and increase efficiency, a high contact strength, low friction coating was applied to the cam and follower surfaces (Magnaplate Nedox FM-5 and Magnaplate Nedox SF-2 respectively) as recommended by the plating manufacturer. These coatings were applied on top of the Vascomax C300 base material. After only a few short operations, an anomaly within the drill auger mechanism was detected. Upon disassembly, it was found that the coatings were in the process of flaking off of the cam as shown in Figure 13. These flakes had become lodged in an open bearing, creating a torque anomaly. As seen in the figure, flaking of the coatings was so bad that it was decided to simply remove the coatings from the area and allow the base material to act as the contact surface. The drill housings were then cleaned and reassembled. This issue has not appeared again, however, it is expected that a small amount of base material is gradually wearing away as the drill is used. The open bearing has since been replaced with a shielded bearing to further minimize the chances of debris migrating into the bearing.

> *Lesson Learned: Honeybee Robotics has attempted to use a number of different coatings for percussive cam and follower mechanisms in the past. Due to the high number of cycles and the high contact stress on the cam and follower surfaces, none of these coatings seem to last more than a dozen drilling operations, where each operation requires at least 10,000 cycles. It is advised that future mechanisms with similar requirements consider not applying any coatings to the surface. It is highly recommended to build a breadboard to test material wear rates if particulate accumulation will cause problems with other mechanisms. In addition, be sure to shield any bearings in the vicinity of such mechanisms. It is likely that the percussive vibration helped migrate particles into the unshielded bearings.*

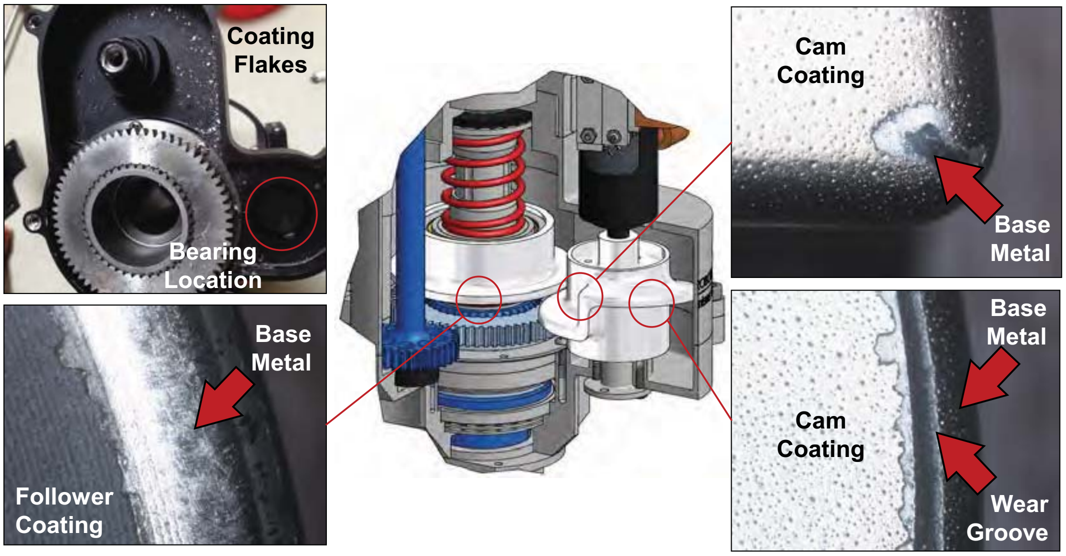

**Figure 13. ROPEC Cam and Follower Coating Issues**

<u>Autonomous Gear Meshing</u>

The ROPEC Drill requires that the Breakoff Cluster Gear be de-meshed from the Breakoff Output Gear during the drilling process, and meshed during the core breakoff routine. This mechanism is shown in Figure 7 and discussed in previous sections. In theory, if the absolute position is known for each of the gears, they can be meshed together after a short calibration. In practice, this method of gear meshing required a significant amount of software development and trial and error during the assembly and integration phase. Ultimately, the software routine is able to position the gears close to where they need to be, then a stepping routine is implemented which incrementally moves the Breakoff Pinion Gear, then raises the Breakoff Cluster Gear using the Pushrod. If Pushrod stall is detected prematurely, the routine repeats, stepping the Pinion Gear a small amount. This routine typically works, but sometimes fails to mesh the gears within the set number of incremental steps. The routine then needs to be run again. This trial-and-error method is not ideal for a flight system.

> *Lesson Learned: Meshing and de-meshing gears is not an ideal choice when designing a high reliability mechanism. If it is a requirement on the mechanism, which is the case for ROPEC, it is recommended that axial meshing / demeshing not be used unless there is very high precision control over the absolute position of each gear. One of the two gears had this amount of control on ROPEC, and meshing is not 100% reliable. If meshing / demeshing is required, a "Missing Tooth" method can be used instead. This method was successfully implemented on a previous coring drill (SASSI Drill), and is shown in detail in Figure 14. Using this method, the absolute position of the Breakoff Cluster Gear and Breakoff Output Gear is known using a set of magnetic absolute position*

*encoders. Both the Breakoff Output Gear and the Breakoff Cluster Gear have one or more missing teeth. As shown in the figure, the Breakoff Output Gear is first oriented in position as shown in (1). At this point, the Auger drivetrain is able to control the position of the Breakoff Output Gear. Both gears are then rotated simultaneously as shown in (2) until they are meshed. As shown in (3), the Breakoff drivetrain can now control the position of the Breakoff Output Gear, allowing the higher torque produced by the Breakoff Actuator to help shear the core.*

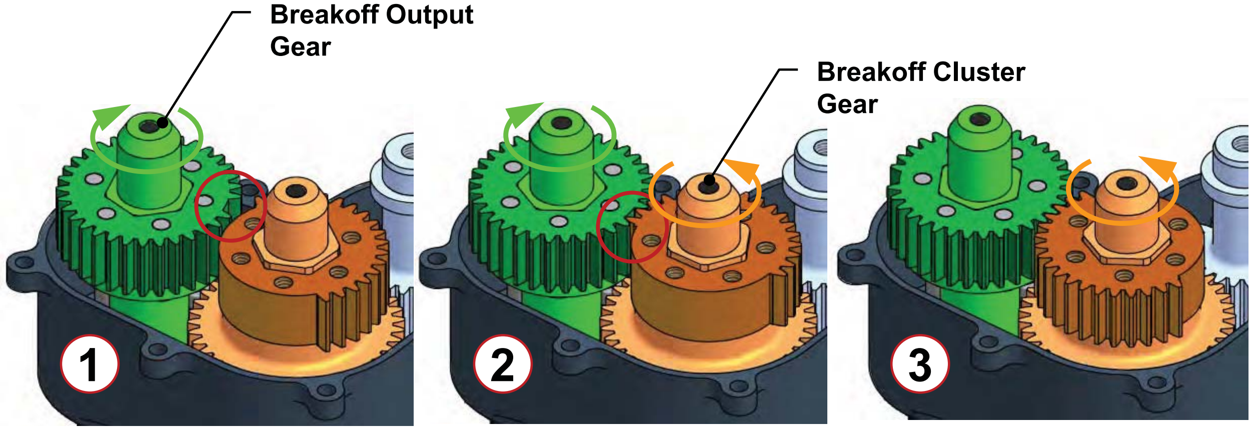

**Figure 14. SASSI Drill Missing Tooth Gear Coupling Method**

## Conclusion

The ROtary Percussive Coring Drill is a light weight, flight-like, five actuator drilling system prototype designed to acquire core material from rock targets for the purposes of Mars Sample Return. The ROPEC Drill is designed to integrate with a “One Bit-One Core” approach to returning samples from the Martian surface. The ROPEC Drill has a number of different attachments which expand its capability to include rock abrasion, brushing, powder and regolith acquisition, and viewing of rock cores for sample triage purposes.

A number of issues have been encountered with the ROPEC drill including flex cable development, coatings under high stress and cyclic loading, and meshing / demeshing of spur gears, resulting in a number of lessons learned which can be applied to similar prototype or flight mechanisms.

The ROPEC Drill has recently been integrated with a five degree of freedom Robotic Arm and mobility system, and has demonstrated docking with a prototype Bit Station, obtaining a Coring Bit, drilling and acquiring a rock core sample, and delivering the bit to a prototype Sample Cache. All drill attachments have similarly been demonstrated from the same platform.

## References

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